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(6) THE PROCESSING RESOURCE DEMANDS OF FAILURE DETECTION IN DYNAMIC SYSTEMS

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ABSTRACT

A conception of human attentional resources is presented that describes these resources, not as an undifferentiated pool of capacity, but as partitioned into separate structure-specific reservoirs related to the processes of encoding, central processing and responding. An experiment is then described in which subjects detected dynamic system failures, either while actually tracking the control dynamics (manual mode), or while passively observing an autopilot controlling the dynamics (automatic mode). Failure detection, the primary task was performed alone, and with each of two structurally different loading tasks: mental arithmetic and a critical instability tracking task. Manual detection and primary task tracking were affected by the critical tracking task but not by mental arithmetic. The opposite pattern of interference was found for automatic detection. Assuming that manual and automatic detection depend upon different information sources, these results are shown to be compatible with the concept of structure-specific resources.

INTRODUCTION

Wickens and Kessel have undertaken a series of investigations that have contrasted two roles of human operator interaction with dynamic systems: as an active controller, and as a passive supervisor/monitor of the system under automatic or autopilot control (Wickens and Kessel, 1977, 1979; Kessel and Wickens, 1978). In this research, a number of processing variables were identified that differed between the two modes. One major point of contrast related to the difference in operator workload imposed by the two levels of participation. It was argued that an obvious potential benefit encurred by removing the human operator from the control loop and thereby replacing manual with autopilot control results from the elimination of the human requirement to select and execute manual responses. At the same time however, it is not apparent that this reduction in "response load" is accompanied by a corresponding reduction in the requirements of display monitoring and updating; that is, the requirement to maintain a level of familiarity with the current state of the system. More specifically this requirement entails perceiving the current parameters of a system (its position and higher derivatives), and revising an "internal model" of the state of the system and of environmental inputs so that malfunctions or changes in state can be rapidly and appropriately responded to. It is argued that the cognitive demands imposed by these processes may be greater than the demands imposed upon the active controller.

Efforts to assess the workload or attention demands associated with visual monitoring have produced somewhat contradictory results. On the one hand, a series of theoretical studies in the psychological literature suggest in general that the attention demands of monitoring for and encoding visually presented information are minimal (e.g., Posner and Boies, 1971; Kerr, 1973; Keele, 1973; Roediger, et al, 1977; Shiffrin and Grantham, 1974). While the research upon which these conclusions were based related primarily to the processing of discrete verbal and non verbal stimuli, investigations of the monitoring of continuous signals by Levison and Tanner (1971) provided some substantiation for those conclusions. These investigators found that monitoring workload (assessed by interference with concurrent activities) was considerably less than the level predicted by a theoretical model of the optimal controller.

In contrast to these conclusions, there exists a considerable body of evidence that implicates relatively heavy demands associated with some kinds of display monitoring. These demands are reflected in the time-critical processing of alpha numeric characters (Schneider and Shiffrin, 1977), the processing of dynamic spatial displays requiring considerable visual scanning (Senders, 1964), as well as the processing of spatial displays in which stimuli lie nearly entirely within foveal vision (Wickens, Israel and Donchin, 1979).

The purpose of the research to be described in this report is to explore in greater detail the nature of the workload or processing demands imposed by the task of monitoring dynamic systems for the occurrence of system failures. Our interest is in establishing whether this task shows greater similarity to the "attentionless" category of monitoring tasks described above, or to that class of perceptual/monitoring tasks that are shown to place reasonably heavy demands upon the operator's limited processing resources If the latter effects are observed then the intent is to investigate systematically the <u>locus</u> of processing demands imposed by the tasks. Before describing the details of the experiment, this report will outline some assumptions that are made concerning the structure of the human operator's attentional resources. These assumptions will provide a theoretical framework for interpreting the experimental results.

A Model of the Structure of Processing Resources

The tactic of approach used here will be to identify the processing demands of monitoring by application of the dual task loading paradigm. To the degree that a concurrently performed task disrupts the monitoring/failure detection task (or vice versa), it is assumed that the latter does in fact demand attention. The converse inference -- that successful parallel performance of detection and loading tasks implicate an <u>attentionless</u> status for the monitoring task -- can not be made as readily. Such an inference is based upon the somewhat dubious assumption that all of the operator's processing resources, attention or capacity, reside within a single "undifferentiated" reservoir (Knowles, 1963, Moray, 1967); This argument can be stated briefly as follows: The loading task demanding resources from this undifferentiated reservoir will affect monitoring performance only if the latter also demands those resources (requires attention). If monitoring performance remains unaffected, it therefore must not demand attention.

A review of the experimental literature however reveals the existence of three categories of phenomena that are incompatible with this undifferentiated capacity view and suggests instead that resources may reside within a limited number of separate reservoirs. These phenomena therefore dictate that caution must be employed in inferring that lack of interference implies a "non attentional" status. The three phenomena will be defined as structural overlap, structural alteration effects, and difficulty insensitivity, and will be described in turn.

Structural Overlap: This phenomenon describes instances in which a given task (A), paired with one concurrent task (B_1) will show greater interference than when it is paired with a different task (B_2), despite the fact that task B_1 may be of lesser apparent difficulty, and thereby presumably demanding fewer processing resources than B_2. The greater interference of B_1 then may be attributed to its structural overlap with task A, (Kahneman, 1973). As an example, Wickens (1976) observed that Tracking (Task A) suffered greater interference when performed concurrently with an "open loop" constant force generation task (Task B_1) than with an auditory signal detection task (Task B_2). Contrary to the interference pattern reflected by the data, subjects reported the signal detection task to be the more difficult of the two (demanding of more resources).

Structural Alteration Effects: These describe instances in which an alteration of some characteristic of a task, for example its input or response modality, that has little or no effect on its single task performance level and produces no change in its apparent information processing demands (task difficulty), can greatly alter its degree of interference with a concurrent task, (e.g., Kantowitz & Knight, 1976; Triesman & Davies, 1974; Harris, Owens, & North, 1978; McLeod, 1978). Presumably, the alteration that is made serves to change the processing structures utilized in task performance, and thereby alters the structural interference with the concurrent task. This phenomenon cannot be accounted for by undifferentiated capacity theory because the alteration by itself produces no change in the demand for the limited resources, and thus should preserve an equivalent level of interference in the two task combinations. As a specific example, Harris, Owens, and North (1978) investigated tracking performed concurrently with a visually displayed digit processing mental arithmetic task. They observed that by changing the response modality from a manual one (subjects entered their responses on a keyboard) to a vocal one, the extent of interference with tracking was dramatically reduced.

Difficulty insensitivity represents the converse of structural alteration and describes instances in which an increase in task difficulty -- one that will produce a deterioration in single task performance, and perhaps a decrement in the performance on one concurrent task -- will fail to induce any change in performance of a different concurrent task (North, 1977; Wickens, Israel and Donchin, 1977; Kantowitz and Knight, 1976). Difficulty insensitivity is clearly incompatible with the undifferentiated capacity theory since, according to this theory the manipulation of difficulty should impose a change on the demand for the available resources, and thereby indirectly alter the performance level of the current task that depends upon those same resources. As one example, of this phenomenon, North (1977) examined the effects of performing discrete digit processing tasks of varying levels of complexity, on concurrent tracking performance. The discrete tasks required operators to perform mental operations of different complexity on visually displayed digits, and indicate their response with a manual key press. In the simplest condition subjects merely pressed the key corresponding to the displayed digit. A condition of intermediate demand required the subject to indicate the digit immediately preceding the displayed digit. In the most demanding condition, subjects were required to perform a classification operation on a pair of displayed digits. While these three operations apparently imposed different demands as indicated by their single task performance, when they were performed concurrently with the tracking task, all three had roughly equivalent disruptive effects on tracking performance.

An elaboration of the undifferentiated capacity view, that accounts for structural phenomena, while preserving the continuous "resource metaphor" that underlies the capacity theory is presented in detail by Wickens (1979) and assumes that human processing resources reside within a number of separate "structure specific" reservoirs.

The implication of this structural specificity is that, as the demands imposed upon any structure are increased by one task, requiring more resources from that structure, interference with a concurrent task will be attenuated to the extent that the two tasks do not utilize the same structures. This then, is the mechanism which accounts for the phenomenon of difficulty insensitivity. Correspondingly, a change in a task's structural characteristics that does not simultaneously alter its quantitative demand for resources will increase the level of interference to the extent that common processing resources between the concurrent tasks are now required where separate ones were used before. In this way, the mechanism accounts for the phenomenon of structural alteration.

Figure 1 presents one hypothetical representation of three distinct processing reservoirs. One is associated with perceptual encoding--making a categorical classification concerning the nature of a visual or auditory input; one is associated with central processing--an amalgamation of processes involving such operations as mental transformations, rehearsal in short term memory, risk evaluation and decision making, and one is involved with the execution of behavioral responses.

Note then two alternative cases. In Case I, both tasks compete for resources from the same reservoirs; increases in the demand of one task will invariably deplete resources in reservoirs used for the other and its performance will fall. Thus, for example, two tracking tasks might be expected to show such a relation. In Case II, however, there is minimal overlap. Such might define the task structure of reading silently while holding a cup of coffee while a passenger in an aircraft. As the difficulty of the passage increases, demanding more resources, performance on the coffee cup "task" will be little impaired.

Considering this scheme in economic terms, as Navon and Gopher (1979, in press) have done, an analogy can be drawn to an industry in which different workers (the resources) are trained in highly specialized skills. For example, an industry might consist of computer programmers, production line workers and managers. None is equipped to perform the others' tasks, and so increases in the demands imposed on, say, production line output cannot be met by calling computer programmers to the shop. Programming efficiency would therefore continue unimpaired despite the increased demand on production, while production performance would fall short of its new demand.

A relatively extensive survey of the experimental literature by Wickens (1979, in press) in which instances of difficulty insensitivity and structural alteration effects were identified, suggested that the simplified three-pool representation portrayed in figure 1, should be elaborated in the following manner: encoding should be divided into separate pools related to auditory and visual inputs, central processing into pools governing verbal vs. spatial processing (perhaps associated with cerebral hemispheres), and responding into pools controlling vocal vs. manual responding (Figure 2).

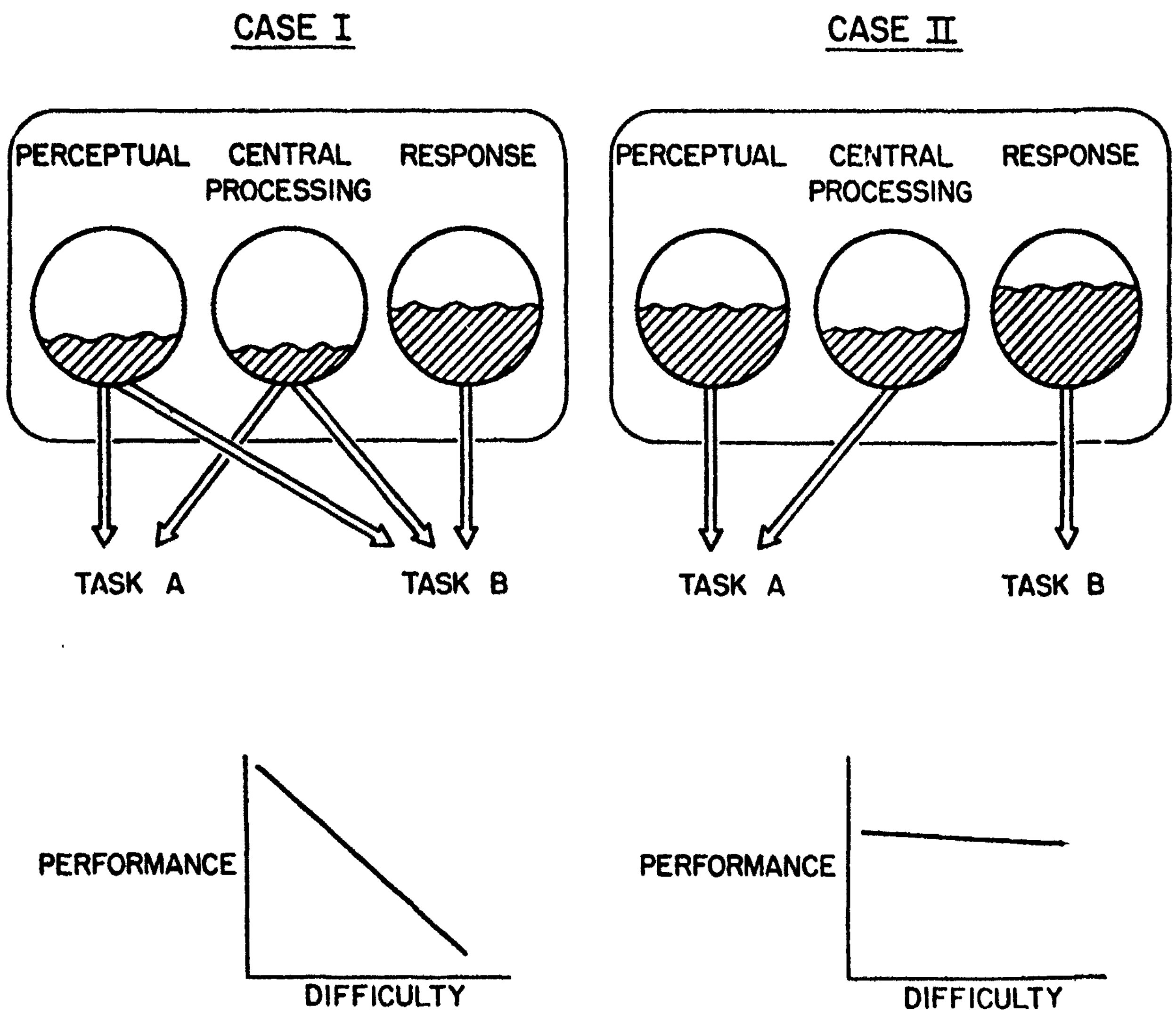

Figure 1. Representation of structure-specific resources predicting difficulty-performance trade offs.

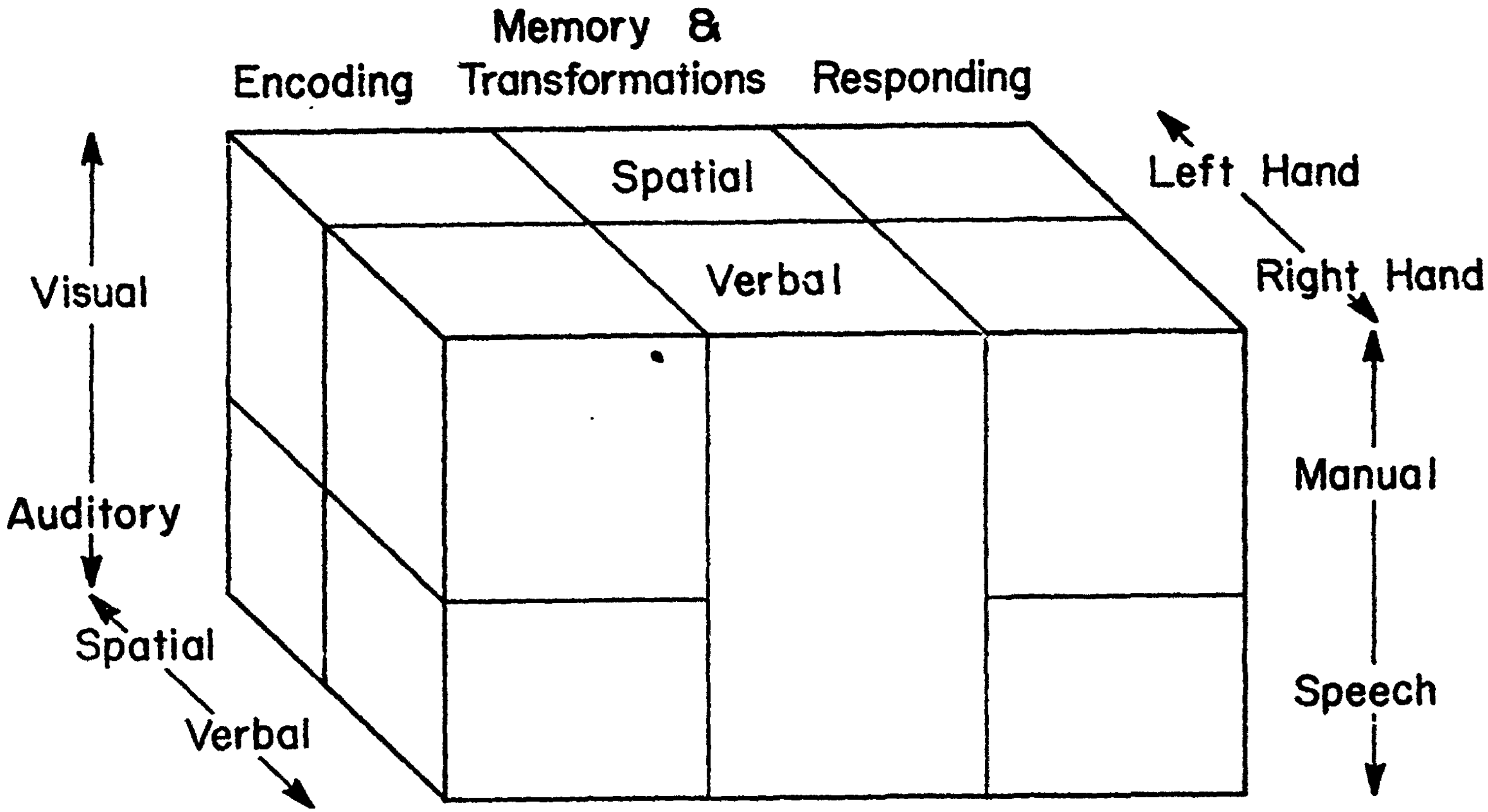

Figure 2. Proposed structural composition of resource pools. (after Wickens, 1979).

Two tasks will interfere to the extent that any of these pools overlap between them. Increases in the difficulty of one task will deteriorate performance of a concurrent one to the extent that the pool demanded by the difficulty increase is utilized by the concurrent task.

Within the framework of the failure detection and monitoring task, the goal of the current research was to evaluate the locus of demand of the monitoring and detection process, by observing changes in failure detection performance, (both in and out of the control loop), when two qualitatively different concurrent loading tasks were imposed and then when their demands were varied. It was hoped that the use of loading tasks that were believed a priori to vary the load on different processing structures, could facilitate an understanding of the processing demands imposed by dynamic system monitoring.

METHOD

The details of the failure detection task that was employed are described in Wickens and Kessel (1977; 1979) and Kessel and Wickens (1978). Briefly however, the subject's task was to detect increases in the second order component of tracking dynamics of the form:

$$Y = K\left(\frac{\alpha}{S^2} + \frac{(1-\alpha)}{S}\right).$$

Step increases in α from a value of .3 to .9 therefore corresponded to failures. Each 2-1/2 minute trial could contain 4, 5 or 6 of these failures interspersed at random intervals. If a given failure was not detected, the dynamics made a 4 second ramp return to the pre-failure value of α. If they were detected the dynamics immediately changed back to the pre-failure value. Subjects indicated their detection of the failure by squeezing a trigger mounted on the tracking control with their forefinger. Latency and accuracy of detection were recorded.

Two different conditions of operator participation were contrasted within the studies to be reported. In the manual or MA condition, subjects manipulated the control stick to make the displayed cursor follow a target moving in 2 dimensions in a low frequency semi predictable path. Cursor position (and therefore error) was determined not only by the subjects control input, but also by a Gaussian disturbance input with an upper cutoff frequency of .32 Hz. The subjects RMS tracking error was recorded as the measure of tracking performance on each trial.

In the AU (autopilot) condition the subject's role in the control loop was replaced by an autopilot whose control dynamics simulated those of the human controller of the first order plant: A pure gain, time delay and added remnant (McRuer and Jex, 1967). In a series of pretests, the parameters of the autopilot were adjusted so that the RMS error of autopilot tracking was equivalent to that produced by the human operator.

The subjects in all conditions received extensive practice and training on the failure detection task before participating in the experimental conditions that were used to generate the data to be reported. The nature of this training is described in Kessel and Wickens (1978). The data that are reported below describe failure detection performance (a weighted average of latency and accuracy*) in both AU and MA conditions as influenced by the concurrent performance of two secondary loading tasks.

<u>Subcritical Tracking Task</u>. In this task (Jex, 1967), subjects were required to manipulate a spring-loaded finger control in the left-right direction with their left hand in order to stablize a system with unstable, positive feedback dynamics of the form:

$$Y = \frac{K\lambda}{S - \lambda.}$$

System out put was indicated by a cursor presented in the middle of the main tracking display, and the control was to be manipulated in such a way as to keep this cursor on a reference point in the center of the screen. The difficulty of the critical task was manipulated by varying the value of the instability constant λ between values of 0.5 and 1.0. Higher values of λ produce greater instability, require more continuous control, and have been validated to demand greater amounts of the operator's limited processing resources (Jex, 1967; Jagacinski, et al, 1978). Critical task performance was assessed by an RMS error measure.

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*Accuracy of detection was determined on each trial using a variant of signal detection theory procedures described in Kessel and Wickens (1978) and Wickens and Kessel (1979). A sensitivity measure (area under the ROC curve, McNicol, 1972) was computed that penalized subjects for both missed failures and false alarms (responses made during periods of normal operation). This accuracy measure was combined with the average response latency to detected failures using a linear weighting to generate a derived performance detection score (DPS). The formula used was: DPS = 10 x A(ROC) - Latency. Higher values of the DPS thereby were produced by more rapid and more accurate detection.

Memory Loading Tasks. Over stereo headphones subjects heard a sequence of pre-recorded two digit numbers occuring every 2 seconds. At unpredictable intervals (on the average of every 15th number), a tone was presented and the subject was required to respond by subtracting the number seven from a preceding digit and verbally report the answer. In the easy condition, seven was to be subtracted from the digit just prior to the probe tone. In the difficult condition, seven was to be subtracted from the digit two positions prior to the probe. The two levels of the memory loading task therefore had the following characteristics. Both required few responses, but placed a continuous demand on memory, and the extent of this memory load was the major variable of interest. Performance was assessed as the accuracy (percent correct) of responses.

It should be noted that both the critical task and mental arithmetic tasks were defined as loading tasks. That is, instructions presented to the subjects stressed that these tasks should be performed as well under dual task conditions (concurrently with failure detection) as under the control conditions in which performance on the loading task alone was assessed. Furthermore it was emphasized that subjects should perform as well on the difficult levels of these tasks as on the easy levels. A system of contingent bonuses, in which good failure detection performance was rewarded only to the extent that these loading task performance criteria were met, was imposed in order to reinforce the effect of the verbal instructions. A summary of the dual task experimental design is shown in figure 3. Participatory mode and loading task were manipulated between subjects.

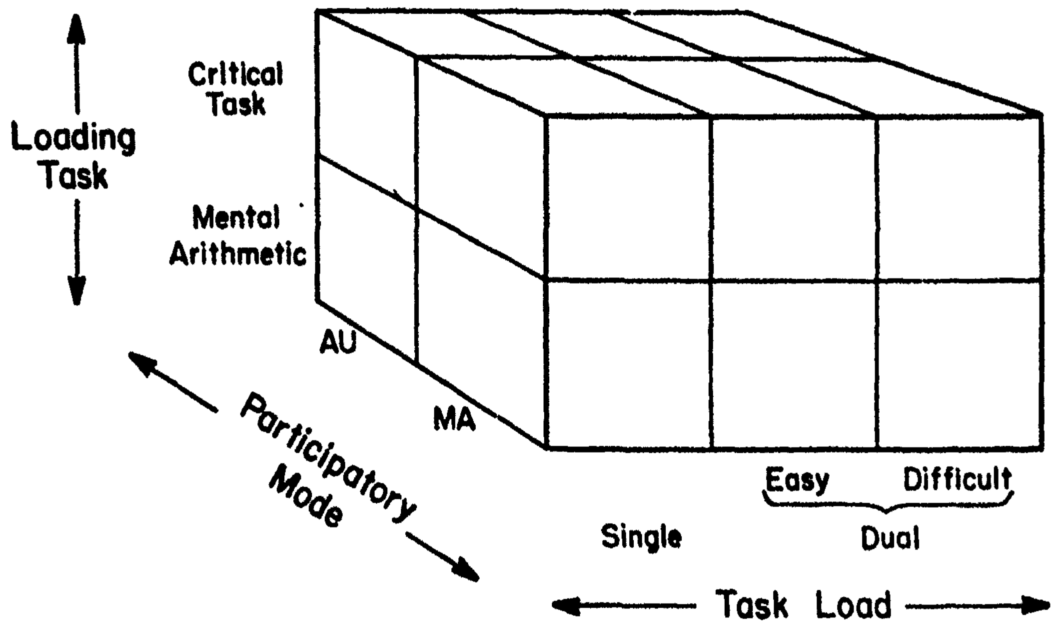

Figure 3. Experimental design.

RESULTS

Failure Detection Data

Performance on the failure detection task (the derived performance score which constituted the weighted measure of detection accuracy and latency) is presented in Table 1 as a function of participatory mode, loading task and level of task load (none, easy, difficult). The performance data on the two loading tasks are shown in Table 2. For reasons discussed below, it is important to consider the effects of the impact of the loading task (e.g., the contrast between single, and dual task detection performance), separately from the effects of increasing loading task difficulty.

Effects of loading task difficulty. The data presented in table 1 suggest the presence of some instances of difficulty insensitivity. Indeed statistical analyses of the contrast between the easy and difficult levels of the two loading tasks in the two participatory modes revealed that only the effect of the critical task difficulty on detection in the MA mode achieved a level of statistical reliability ($t_{11} = 2.72$, $p < .05$). AU detection was uninfluenced by critical task difficulty, while the mental arithmetic task loading failed to influence detection in either mode.

Considerable caution however must be exercised in considering these negative results as evidence for separate processing reservoirs as outlined on p. 4. While the presence of an effect (as observed with MA detection and the critical loading task) can clearly be interpreted as resulting from a competition between tasks for resources, the absence of an effect does not necessarily imply the absence of competition. Indeed it may be asserted that increasing loading task difficulty does consume more of the operator's limited processing resources only to the extent that at least one of two effects are observed: (1) loading task performance remains constant as its difficulty increases in the dual task condition, thereby insuring that more resources are required to maintain equivalent performance on the more difficult task. (2) The same loading manipulation is observed to influence performance on a different time-shared task. If neither of these claims can be made, then a conservative interpretation must be offered that the operator has preserved the same allocation policy of resources between the loaded task (here failure detection) and the loading task under easy and difficult loading conditions. Under difficult conditions the loading task receives no more resources and therefore shows a deterioration in performance, while the loaded task,

Table 1

Derived Performance Score

[10 x A(ROC)[a] - Latency[b]]

Mode	Loading Task	Single Task	Dual Task Easy	Dual Task Difficult
AU	Mental Arithmetic	5.22	4.67	4.77
	Critical Task	4.68	4.65	4.63
MA	Mental Arithmetic	6.79	6.80	6.73
	Critical Task	6.61	6.03	5.85

Tracking RMS Error

Loading Task	Single Task	Dual Task Easy	Dual Task Difficult
Mental Arithmetic	.12	.11	.11
Critical Task	.11	.16	.17

[a]A(ROC) is non-parametric detection sensitivity measure of area under the ROC curve. Range in value from 0.5 (chance performance) to 1.0 (perfect performance).

[b]Latency in seconds.

Table 2

Loading Task Performance

Mode	Loading Task	Measure	Easy	Difficult
AU	Mental Arithmetic	(% correct)	97	90
MA			96	82
AU	Critical Task	(RMS Error)	0.03	0.04
MA			0.06	0.08

also receiving the same supply in easy as in difficult conditions will show no change, (Roediger, Knight and Kantowitz, 1977).

Consideration of the data in Table 2 indicated that the first of these conditions was not observed. In both modes, performance on both loading tasks deteriorated with the increase in loading difficulty. Despite experimental instructions, subjects appeared unable to maintain performance on the difficult task at a level equivalent to its value on the easy task.[1] However the second claim can be made insofar as critical task difficulty was observed to effect performance on the primary tracking task in the MA condition (see below). The assertion can therefore be made that the increase in critical task instability, demanding more processing resources, reduced detection performance in the MA mode, but not in the AU mode.

Impact of Loading Task. To evaluate the impact of the two loading tasks on detection performance, the detection data for each subject were collapsed across the two levels of task difficulty and, along with the single task data were subjected to a 2 (loading task) X 2 (mode) X 2 (level of load--single vs. dual) X 6 (subjects) ANOVA. Loading task and mode were of course between subject variables while task load varied within subjects. The data for the eight conditions are presented in figure 4. In the ANOVA, statistically reliable effects were obtained for mode ($F_{1,20} = 52.69$, $p < .001$), task load ($F_{1,20} = 6.47$, $p < .02$) and for the three way interaction of load X loading task X mode, ($F_{1,20} = 11.01$, $p < .01$). The effect of mode, indicating superior detection in the manual mode was not surprising, and replicated findings reported in earlier results (Wickens and Kessel, 1977, 1979; Kessel and Wickens, 1978). The reliable effect of task load, manifest as a general decrease in detection performance resulting from the introduction of the loading tasks is also expected. Presumably the loading tasks demand processing structures and/or consume processing resources that are also utilized for failure detection. The requirement to share these resources leads to a deterioration in detection performance.

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[1]Even in the absence of loading performance constancy, it is possible to argue that the difficult level consumed more resources than the easy if dual task performance on the difficult task stayed closer to its single task equivalent than did dual task performance on the easy task (e.g. loading task performance decrements were smaller for the difficult than for the easy level). However in the current data, single task loading task performance was assessed only on the initial training day. Thus, because of practice confounds, it is impossible to compare it with the later dual task values.

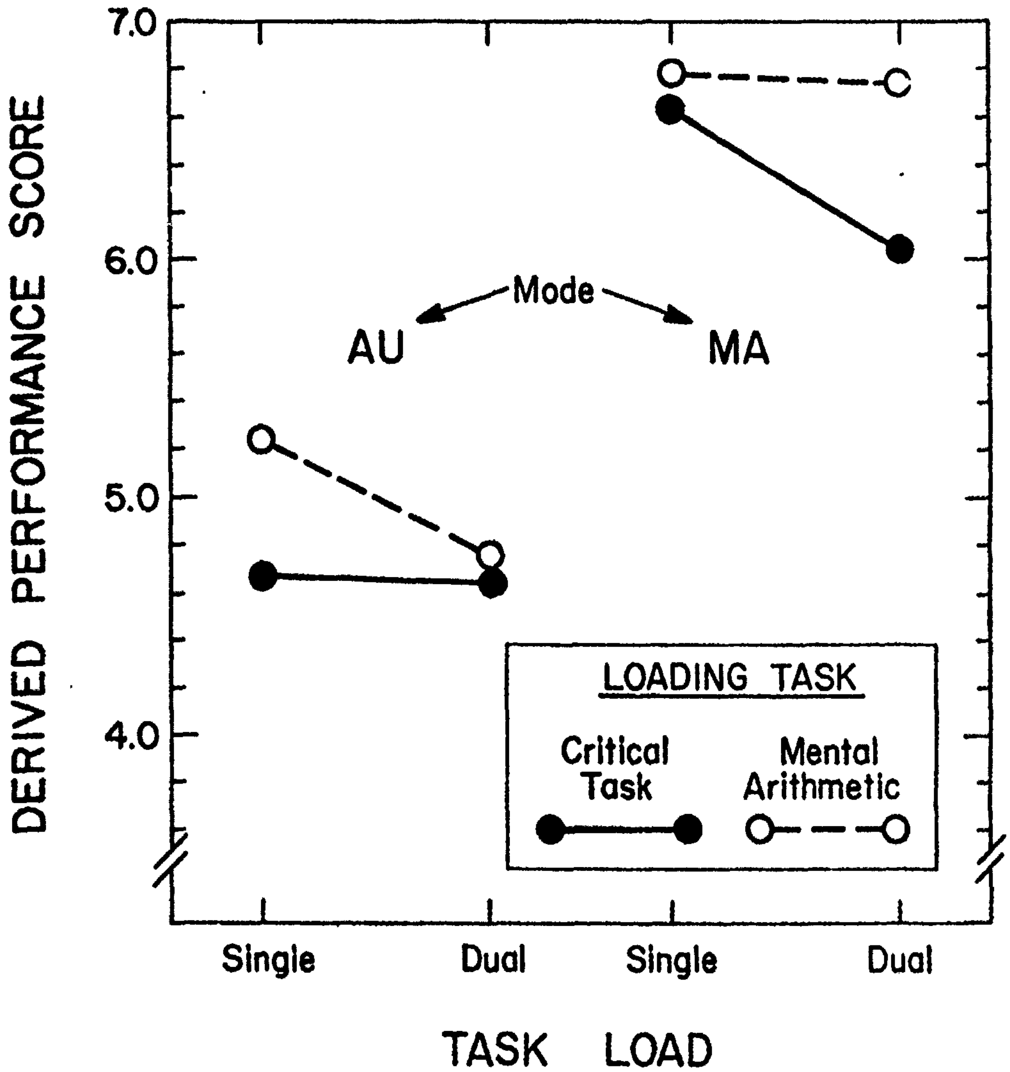

Figure 4: Impact of the two loading tasks on AU and on MA failure detection performance. Derived performance score is a weighted speed-accuracy measure.

Of considerable interest however is the particular form demonstrated by this dual task detection decrement, manifest in the reliable three way interaction. AU detection is adversely affected by the mental arithmetic task but not by the critical tracking task, while MA detection performance shows precisely the converse effects. The interpretation of this interaction will be discussed below.

Manual mode tracking data. RMS error on the primary tracking task--that task in which failures occurred--is presented at the bottom of Table 1. (Tracking error in the AU condition is not reported since the computer controlled performance is obviously unaffected by the processing demands imposed upon the subject by the loading track.) The apparent influence of the critical task upon tracking performance is substantiated by a two way (subject X load) ANOVA that produced a reliable main effect of task load ($F_{2,20}$ = 46.0, $p < .01$). Tukey tests of the difference between single and dual task RMS error, and between the easy and difficult levels of the critical task revealed both effects also to be statistically reliable ($p < .01$ and $p < .05$ respectively). Table 2 also indicates, and statistical analyses substantiated that the effect of the mental arithmetic task on tracking performance was minimal, and not statistically reliable ($p > .10$).

DISCUSSION

The original intent of the research described above was to assess the workload demands associated with monitoring, both in terms of the magnitude of these demands and in terms of the locus of their effect. The logic underlying the experimental procedure asserted that, to the extent that a loading task interfered with failure detection, either upon its introduction or with an increase in its demand, then the detection task demands attention, and furthermore the attentional resources associated with this demand are consonant with the demand characteristics of the loading task.

Two separate loading tasks were chosen. Within the framework presented in figure 2, the mental arithmetic task was selected to ensure a heavy processing demand on the central processing stage (memory and transformations), while posessing input (auditory) and output (vocal) modalities that were as disparate as possible from the input-output demands of failure detection (visual monitoring/manual responding). Conversely the demands of the critical tracking task were precisely those of visual encoding and manual responding, while it was assumed that the central processing demands would be somewhat diminished relative to the mental loading task.

Because the difficulty manipulations of task load proved to be somewhat ambigous in their effect, due to subject's inability to sustain constant loading task performance, the discussion below will focus primarily on the effects of loading task introduction; that is, upon the data presented in figure 4. These data clearly support the claim that the failure detection task demands some portion of the operator's limited attentional resources. When these resources were diminished by the introduction of the loading task, detection performance deteriorated. An interesting difference, highlighted by the reliable three way interaction was observed between the two loading tasks in terms of their differential effects on MA vs. AU detection. AU detection was derogated most by the mental arithmetic memory task, while MA detection showed great competition for resources with the critical tracking task.

These results are compatible with the multiple reservoir concept presented above in figure 2. Considering first AU detection, it is apparent that the visual and motor load imposed by the requirement to perform the critical tracking task did not compete for resources utilized in detection, despite the maximum similarity between the tasks in their input (visual spatial encoding) and output (manual responding) requirements. In accounting for this negative result it cannot be argued that the detection task was data limited[1], since introduction of the other loading task (mental arithmetic) produced a reliable deterioration in detection performance.

Correspondingly it is difficult to argue that the mental arithmetic task was simply more difficult than the critical task, and demanded more processing resources from an undifferentiated pool of capacity. Were this the case, then mental arithmetic should show greater interference with other tasks as well. Yet manual tracking performance, was effected less by introduction of the arithmetic task, than by introduction of the critical task. In fact, tracking was altogether insensitive to the presence or absence of mental arithmetic.

The results are consistent if it is assumed that the AU detection process --the comparison of incoming data with an internal model of the normally functioning system, and application of appropriate decision rules to initiate the

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[1]Dependent upon the quality of data available and not affected by the availability of attentional processing resources (Norman and Bobrow, 1975).

response--depends upon resources residing in the reservoirs labelled either encoding or memory and transformations in figure 2. The mental arithmetic task also demands central processing resources.

In contrast the critical task, whose dynamics and required transformations are those of a relatively simple first order system does not heavily load these reservoirs. Its resource demands do not compete with those of AU detection, but apparently draw from the response related reservoir depicted in figures 1 and 2. This view is consistent with the results of a series of investigations in which tracking has been paired with secondary tasks that elicit evoked brain potentials (Wickens, Isreal and Donchin, 1977; Isreal, 1978). In these investigations, the evoked potentials, assumed to be independent of response-related factors since no overt responses are required for their elicitation, are found to be quite insensitive to a variety of manipulations of tracking difficulty.

One result that appears at first to be anomalous concerns the loading effects that were observed on MA detection. Unlike detection in the AU modality, MA detection was influenced by the response loading critical task, and was unaffected by mental arithmetic. Two possible explanations may be offered to account for this difference. (a) MA detection is dependent upon the quality of visual information extracted from the display and this in turn depends upon the level of tracking performance. Since tracking performance was disrupted both by the requirement to perform the critical task, and by the increase in critical task difficulty, it might be anticipated that detection performance would deteriorate in a corresponding manner, in response to an increasingly "noisy" data source (more variable tracking error). This explanation however fails to explain why MA detection remained unaffected by mental arithmetic.

(b) The second explanation is more compatible with the structure specific resource view proposed above and is based upon the assumption that AU and MA detection involve qualitatively different operations. Wickens and Kessel (1977, 1979) have argued that MA detection depends in part upon the processing of proprioceptive information[1] related to the subject's initial adaptive

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[1] This may include either the proprioceptive feedback from the peripheral receptors in the hand and arm, or the central knowledge of motor commands that are issued to the effectors. The latter category of information is sometimes referred to as efferent copy (Pew, 1974).

response to a failure. AU detection of course relies only upon sources of visual information, and it is the additional proprioceptive information channel in MA detection that is, in part responsible for its superiority. According to this interpretation of task loading effects, the processing of this response-related proprioceptive information in MA detection is disrupted by the demand for response resources of the critical task, but is unaffected by the central processing demands of mental arithmetic. Conversely AU detection, dependent only upon visual information is unaffected by response-related critical task demands but is disrupted by the demands on the central processing pool imposed by mental arithmetic. Whether the actual demands of AU detection are related to central processing, or to encoding cannot be precisely determined, but the absence of an influence of central processing load (mental arithmetic) on MA detection, suggests that the central processing demand of detection may not be extensive.

In summarizing this interpretation, it will be noted that the concept of processing stages has been uncoupled from that of processing reservoirs. This uncoupling is portrayed in figure 5 and suggests that two separate stages of processing (perceptual encoding and central processing) both rely upon a common reservoir of resources[1]. Some evidence for the commonality of resource demands of those stages is provided by investigations in which detection and memory tasks are found to exhibit considerable mutual interference and to show corresponding performance-difficulty tradeoffs (e.g. Shulman and Greenberg, 1971). In contrast, the response stage draws resources from its separate reservoir. The critical task relies upon the response reservoir as does MA detection while the mental arithmetic task and AU detection depend upon central processing/encoding resources. These relations are depicted in figure 5.

The interpretation presented above is certainly not definitive, and alternate explanations of the data could be offered. However it should be emphasized that the framework within which this interpretation is proposed--the concept of multiple reservoirs that supply stages with processing resources--is consistent with many findings in the experimental literature that are summarized by Wickens (1979a), and in a more general way with theories proposed by Navon and Gopher (1977; 1979), Sanders (1979), and Roediger, et al, (1977).

[1]The above interpretation has not considered the extent to which different modalities (visual vs. auditory input and vocal vs. manual responding) may define separate processing reservoirs within processing stages, as suggested in figure 2. Evidence cited on p. 3 suggests that this may be the case. However these considerations are not necessary for interpreting the present data, and so the framework for analysis is the more simplified structure of figures 1 and 5.

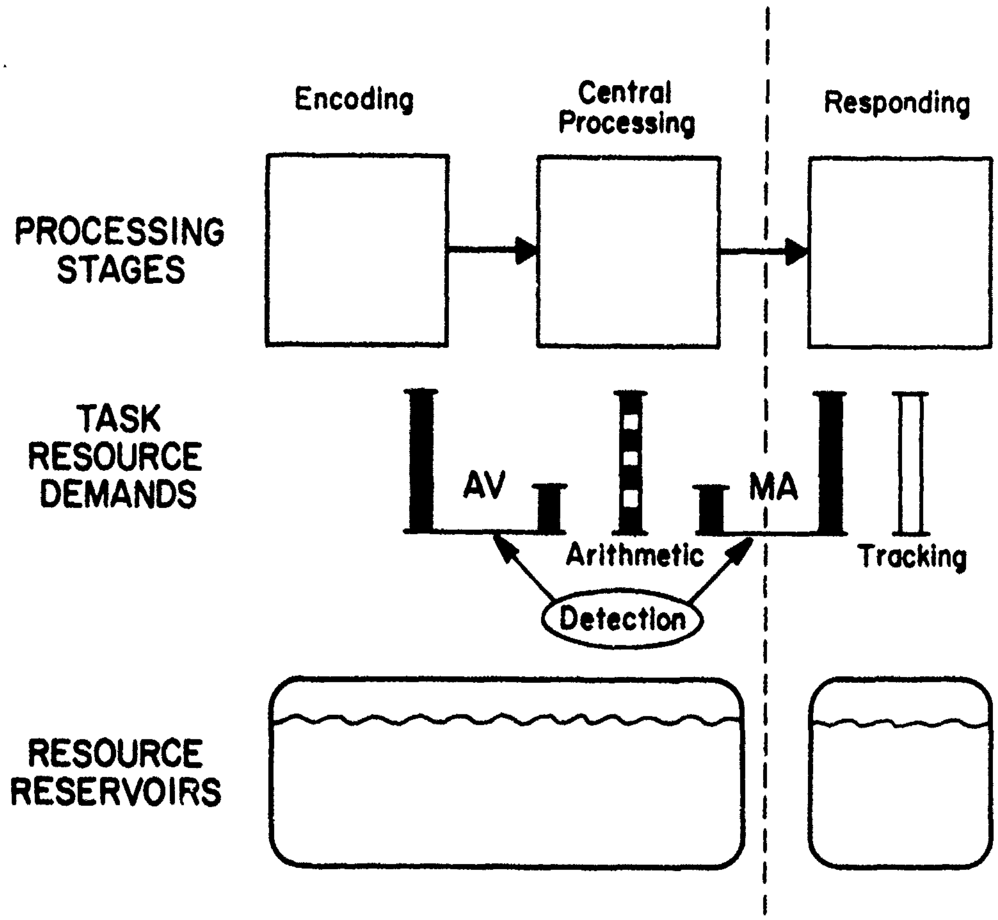

Figure 5: Representation of the relation between processing stages, task demands, and processing resource reservoirs.

The discussion above has considered the results within the framework of structure-specific resources. It is also instructive to consider the data within the context of the two categories of research findings described in the introduction; those that have attributed monitoring/encoding to an attentionless status, and those that have not. The monitoring/failure detection task investigated in the paradigm described here appears to fall conclusively into the latter category.

Two characteristics of the task seem to differentiate it from examples of the attentionless monitoring. (a) Overt decisions were required here, thus distinguishing this task from those of a pure monitoring nature. Monitoring tasks have been argued to demand minimal resources only as long as a discrete decision to respond is not required (e.g., Kahneman, 1973; Moray and Fitter, 1973). (b) In the present task, the amount of signal processing required to distinguish the failed from the normally operating state was not trivial. It generally exceeded for example the demands of detecting super threshold visual or auditory events, or of recognizing letters or familiar words (Keele, 1973). Thus despite the moderate level of training provided to subjects in this investigation, it would be hard to assert that they were equipped with a highly developed representation in memory of the state of the failed system such that the stimulus evidence provided by the failure could automatically and pre-attentively contact the memory representation (Keele, 1973; Kerr, 1973; LaBerge, 1973; Schneider and Shiffrin, 1977). Nor could failures here be registered by detecting a highly salient visual feature such as an intensity increase (Shiffren and Grantham, 1974), or the excursion of a display symbol beyond a given spatial limit (Levison and Tanner, 1971). It is probable that such automatic, pre-attentive detection of dynamic system failures might eventually develop provided that subjects received a sufficiently high level of training either in the failure detection task or in controlling the system in its failed state. This level of familiarity is probably typical of the pilot's knowledge of the normal operating dynamics of an aircraft that he has been trained to fly.

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